INFLUENCE OF ELEVATED TEMPERATURE ON MECHANICAL PROPERTIES AND DURABILITY OF CONCRETE

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ABSTRACT

Concrete structures are exposed to high temperatures during fire. Bothe the mechanical properties and durability after exposed to elevated temperatures are of great importance in terms of the serviceability of buildings. In this project, the effects of elevated temperatures (20, 100, 200, 300, 400, 500 and 600 ℃) on the compressive strength, elastic modulus, fracture energy, water capillary absorption and chloride penetration have been studied. The influence of cooling methods on these properties has been also investigated. The results obtained indicate that when the temperature is below 400 ℃ for concrete A (W/C=0.4) and 300 ℃ for concrete B (W/C=0.5) with natural cooling, the compressive strength did not decrease immediately. But with water splashing cooling, the compressive strength of concrete lost approx. 20 % at 300 degree. The elastic modulus of concrete decreased gradually with the increasing of temperature. And there is no real difference between two types of cooling methods. When the temperature is over 400 degree only, the fracture energy decreased significantly. After exposed to elevated temperatures, concrete absorbed much more water and chloride ions, which bring a high risk for RC structures. This effect shall also be taken into consideration when concrete structures after fire is evaluated.

KEYWORDS
Elevated temperature, concrete, compressive strength, elastic modules, fracture energy, water capillary absorption, chloride penetration

INTRODUCTION

Concrete is used extensively throughout the world. The applications of such concretes are increasing day by day due to their superior structural performance, environmental friendliness, and energy-conserving implications (Mehta 1999). Apart from the usual risk of fire, these concretes are exposed to high temperatures and pressures for considerable periods of time in the abovementioned industries. Although concrete is generally believed to be an excellent fireproofing material, many recent studies have shown extensive damage or even catastrophic failure at high temperatures (Phan 1996). The mechanical properties such as strength, modulus of elasticity and volume stability of concrete are significantly reduced at high temperatures. This may result in undesirable structural failures (Ali *et al*. 2004; Janotka and Nurnbergerova 2005; Sanad *et al.* 2000; Cioni *et al.* 2001; Poon *et al.* 2004; Georgali and Tsakiridis 2005). Most researchers believe that the concrete compressive strength increases at around 200□; at about 400□, it begins to decay and 400~800□ temperature ranges is the major loss of strength which is 400~600□ strength decreases fastest segment (Poon *et al.* 2001; Peng *et al.* 1999; Li *et al.* 2002; Ghan *et al.* 1999).

The repair and reinforcement of concrete structures after fire is generally based on the evaluation of mechanical properties. But in fact, the durability of concrete materials after exposed to elevated temperatures decreases more significantly than that of mechanical properties (Yan *et al.* 2005; Sun *et al.* 2003). In recent years, the deterioration of durability of concrete after elevated temperatures has been concerned by the engineering field. However, the experimental research in this field is rare. Therefore in this project, the effect of elevated temperatures both on the mechanical properties, water capillary absorption and chloride penetration of concrete were studied in particular.

MATERIALS AND METHODS

Materials and Preparation of Test Specimens

The specimens were prepared with two types of concrete. The compositions of the two types of concrete are shown in Table 1. Ordinary Portland cement type 42.5, crushed limestone with a maximum grain size of 25 mm and river sand with a maximum grain size of 5 mm were used. Cubes with the side length of 100 mm and prisms with the dimensions of 100 mm × 100 mm × 515 mm were prepared. All the samples were demolded after 24 hours and then stored in a humid room with RH ≥ 95 % and temperature of 20 ± 2 ℃ until they have reached an age of 28days.

Table 1 Mixture proportion of the concrete (kg/m^3)

	Cement	Sand	Gravel	Water	Superplasticizer
A (W/C=0.4)	380	579.1	1269	152	4.9
B (W/C=0.5)	320	653	1267	160	3.8

Elevated Temperature and Cooling Methods

The specimens were taken out from the curing room after 28 days and placed in a room with temperature of 20 □ and humidity of 50 % for 7 days. After that, the specimens were put in the oven and were heated up to 100, 200, 300, 400, 500, 600, 700 and 800 □, respectively, for three hours. Then the specimens were taken out of the oven to cool them down. The cooling methods include natural cooling in the lab climate and fast cooling by splashing water on the specimens' surfaces. For the two types of cooling methods, it is denoted by '-N' for natural cooling in the air and '-W' for water splashing cooling, respectively, in the following text.

Measurements of Mechanical Properties

After cooling down by natural cooling or water splashing cooling, the compressive strength of specimens exposed to different temperatures were measured. In each case, the compressive strength was the average value of three samples. In the meantime, the relative elastic modulus of concrete specimens before and after exposed to elevated temperature had been measured by ultrasonic method. When the ultrasonic wave encounters defects that exit in concrete due to elevated temperature, the transmission will be slowed down. Therefore, the internal defects of concrete can be evaluated by measuring the velocity of ultrasonic wave in concrete. The dynamic elastic modulus can be then calculated by Eq. 1.

$$E_{\mathrm{d}} = \frac{(1+\upsilon)(1-2\upsilon)\rho V^2}{(1-\upsilon)} = \frac{(1+\upsilon)(1-2\upsilon)\rho L^2}{(1-\upsilon)t^2} \tag{1}$$

Where, E_{d} is the dynamic elastic modulus; V is the velocity of ultrasonic waves; t is the transmission time; L is the transmission distance; ρ is the density of the concrete specimen and υ is the Poisson's ratio.

In addition, the fracture energy of concrete before and after exposed to elevated temperature had been also determined by three-point bending test (RILEM). In this way, the deterioration of concrete specimens due to the elevated temperature can be evaluated.

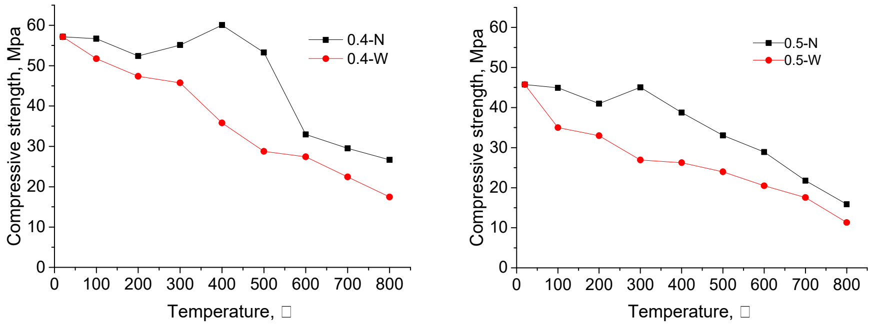
Water Capillary Absorption and Chloride Penetration

Before and after exposed to elevated temperatures, water capillary absorption of two types of concrete had been also measured. Before the test all surfaces were covered with self adhesive aluminium foils except to the contact surface with water and the opposite surface. After that, the specimens were placed in contact with water to conduct water absorption test. In this way, water will penetrate into the specimens in one dimension. Then the amount of water absorbed at the contact time of up to 7 days had been measured by gravimetric method. For some specimens water was replaced by 3.5 % NaCl solution to investigate the chloride penetration into the concrete after exposed to elevated temperature. At a certain time of chloride penetration, the specimens was taken out and grinded from the contact surface mm by mm. Then the chloride concentration in different tested concrete had been determined by titration method.

RESULTS AND DISCUSSION

Influence of Elevated Temperature on Compressive Strength

The results of compressive strength of the two types of concrete before and after exposed to elevated temperatures are shown in Figure 1. It can be learned from the results that, in general, both for concrete A and concrete B the compressive strength after water splashing cooling decreased with the increasing of temperature. But when the temperature is below 400 ℃ for concrete A (W/C=0.4) and 300 ℃ for concrete B (W/C=0.5) after natural cooling, the compressive strength of concrete did not decrease immediately. This means with natural cooling after exposed to a certain high temperature concrete was not damaged yet. While after that, serious deterioration for the microstructure of concrete was determined. If water was splashed on the surfaces after exposed to high temperature, concrete was more damaged due to the thermal stresses caused by the cold water.

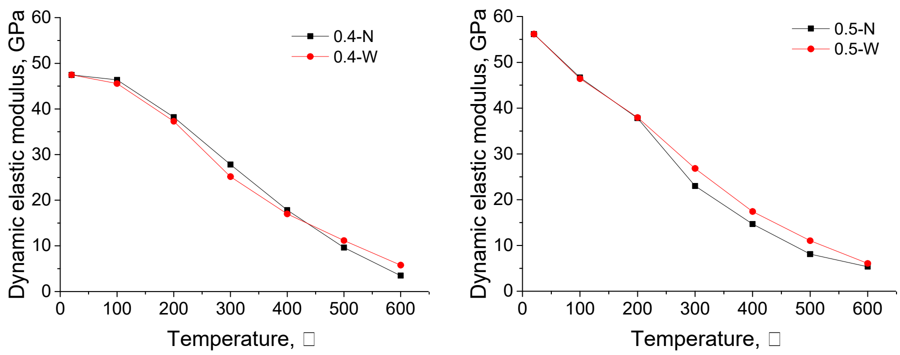


(a) Concrete A (b) Concrete B

Figure 1 The compressive strength of concrete after exposed to elevated temperature

Influence of Elevated Temperature on Elastic Modulus

The elastic modulus of concrete after exposed to elevated temperature has been determined. The results after natural cooling and water splashing cooling are shown in Figure 2. It can be learned that after exposed to elevated temperature micro cracks were formed in concrete and ultrasonic sound would need more time to transmit. Therefore, the elastic modulus was decreased gradually with the increasing of temperature both for concrete with natural and water cooling. But it seems there is no pronounced difference between two types of cooling methods. And water cement ratio is not sensitive either.

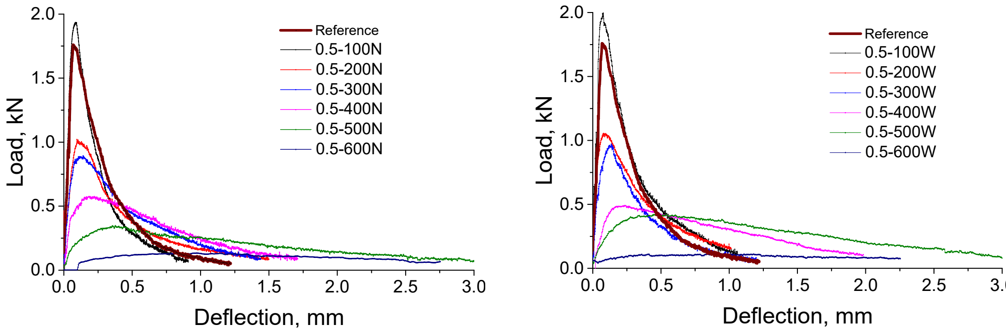


(a) Concrete A (b) Concrete B

Figure 2 The relative elastic modulus of the two types of concrete after exposed to elevated temperature

Influence of Elevated Temperature on Fracture Energy

Three points bending test has been performed to investigate the influence of elevated temperature on fracture energy. The load-deflection curves of the concrete after exposed to different temperatures are shown in Figure 3. The results indicate that with increasing of temperature, the load capacity decreased, but the maximum deflection get increased. With different cooling methods, the load-deflection curves show no much difference. The fracture energy of concrete has been further calculated by means of the program Consoft. The results are listed in Table 2. It can be learned that below 400 degree, the fracture energy calculated from the load-deflection curves does not decrease generally. Only after the temperature is over 400 degree, the fracture energy decreased significantly.



(a) Natural cooling (b) Water splashing cooling

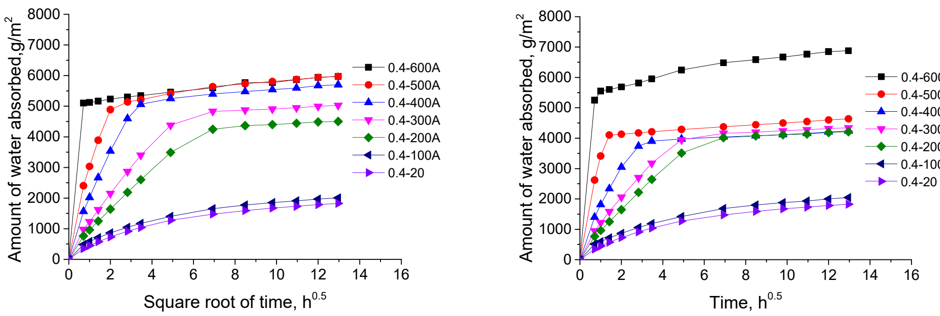
Figure 3 The load-deflection curves of concrete B after exposed to elevated temperature and (a) natural cooling and (b) water splashing cooling

Table 2 Fracture energy of concrete after elevated temperature (N/m)

Temp. □ / Cooling methods	20	100	200	300	400	500	600
Natural cooling	115.4	136.62	118.57	107.51	114.04	64.674	42.48
Water cooling	115.4	105.68	106.8	102.56	112.11	64.9	33.742

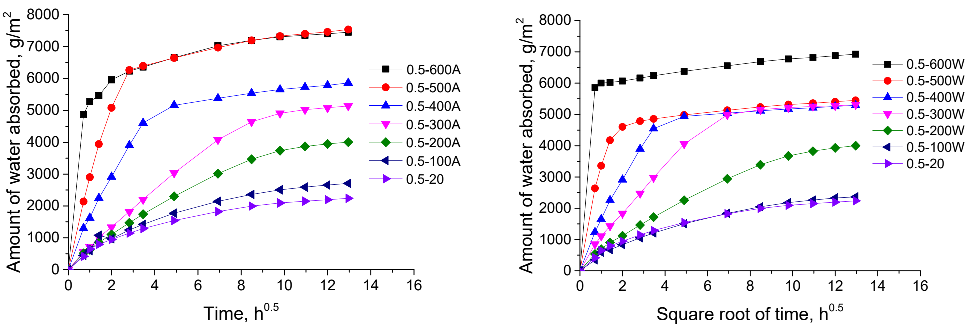
Influence of Elevated Temperature on Water Capillary Absorption

Numerous studies (Zhao *et al.* 1996; Khatri *et al.* 1997; Wang and Li 2003) show that water transportation play an important role in most of deterioration mechanisms of reinforced concrete structures. In this project, water absorption test has been performed in order to study the influence of elevated temperature on this property. The amounts of water absorbed at different absorption time had been measured. The results are shown in Figures 4 and 5 for concrete A and B, respectively. It can be seen from the results that both for concrete A and B, with the increasing of temperature, the amount of water absorbed increased. This means more capillary pores were formed under high temperatures. The slope of the beginning of the curves is considered to be the rate of water absorption, which is also called the coefficient of water capillary absorption. The results are further shown in Figure 6. It can be learned that the coefficient of water capillary absorption increased rapidly.



(a) Natural cooling (b) Water splashing cooling

Figure 4 The amount of water absorbed of concrete A at different time after exposed to elevated temperature and (a) natural cooling and (b) water splashing cooling



(a) Natural cooling (b) Water splashing cooling

Figure 5 The amount of water absorbed of concrete B at different time after exposed to elevated temperature and

(a) natural cooling and (b) water splashing cooling

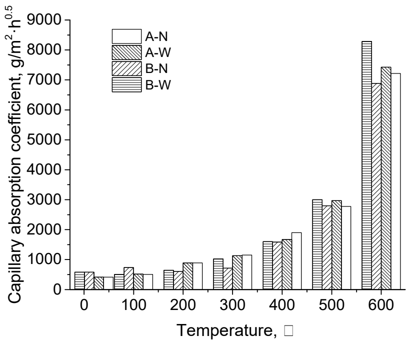


Figure 6 The coefficient of water capillary absorption of concrete after exposed to elevated temperatures

The maximum amount of water absorbed is usually considered to be the water absorption capacity. These results are further shown in Figure 7. With higher water cement ratio, concrete has more capillary pores and thus has higher water capacity. After exposed to elevated temperature, the porosity of concrete was also increased and has much higher water absorption capacity. For instance, the water absorption capacity of concrete A was increased from about 2000 g/m^2 at 20 degree up to approximately 7500 g/m2 at 600 degree.

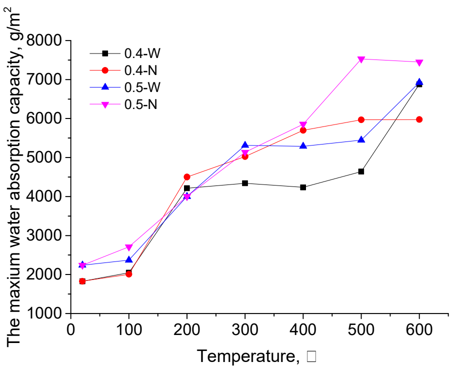
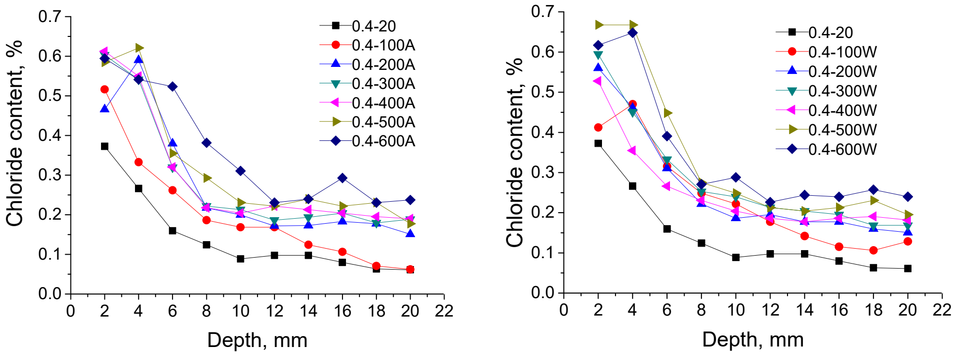


Figure 7 The water absorption capacity of concrete A and B after exposed to elevated temperatures

Influence of Elevated Temperature on Chloride Penetration

After exposed to elevated temperatures, concrete has been put in contact with 3.5 % NaCl solution for 7 days. After that the chloride concentration related to the mass of concrete were measured by titration method. The results are shown in Figure 8. This indicates again that after exposed to elevated temperature, the microstructure system of concrete was damaged and therefore more salt solution penetrated into concrete.



(a) Natural cooling (b) Water splashing cooling

Figure 8 Chloride profiles in concrete A after exposed to elevated temperatures and after (a) natural cooling and (b) water splashing cooling

CONCLUSIONS

- When the temperature is below 400 □ for concrete A (W/C=0.4) and 300 □ for concrete B (W/C=0.5) after natural cooling, the compressive strength did not decrease immediately. But in the case of water splashing cooling, the compressive strength of concrete lost already approx. 20 %. The elastic modulus of concrete decreased gradually with the increasing of temperature. But there is no real difference with two types of cooling methods.

- With the increasing of temperature, the load capacity of concrete under three point bending decreased, but the maximum deflection get increased. With different cooling methods, the load-deflection curves show no much difference. Below 400 degree, the fracture energy does not decrease generally. When the temperature is over 400 degree only, the fracture energy decreased significantly.
- This project also studied the influence of elevated temperature on water and chloride penetration into concrete, which is relevant to the durability of concrete. After exposed to elevated temperatures, concrete absorbed much more water and chloride ions, which bring a high risk for RC structures. This effect shall also be taken into consideration when concrete is reused after fire accidents.

ACKNOWLEDGMENTS

The authors gratefully acknowledge financial supports of ongoing projects by National Basic Research Program of China (no. 2015CB655100) and National Natural Science Foundation of China (nos. 51420105015, 51278260).

REFERENCES

Ali F, Nadjai A, Silcock G, Abu-Tair A (2004). "Outcomes of a major research on fire resistance of concrete columns". *Fire Safety Journal*, 39, 433–45.

Cioni P, Croce P, Salvatore W (2001). "Assessing fire damage to r. c. elements". *Fire Safety Journal*, 36: 181–99.

Feng Naiqian, Xing Feng (2009). "Durability of concrete and concrete structures". *Machinery Industry Press,* Beijing, 223-25.

FMC—50, Determination of the fracture energy of mortar and concrete by means of three Point bending tests on notched beams, RILEM Recommendation, Materials and Srruetures18, 1985: 285-290.

Georgali B, Tsakiridis PE (2005). "Microstructure of fire-damaged concrete". *Cement and Concrete Composition*, 27: 255–9.

Ghan Y N, Peng G F, Anson M (1999). "Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures". *Cement and Concrete Composites*, 21 (1): 23-27.

Janotka I, Nurnbergerova T. (2005). "Effect of temperature on structural quality of the cement paste and high-strength concrete with silica fume". *Nuclear Engineering and Design*, 235: 2019-32.

Khatri R. P., Sirivivatnanon V., Yu L. K. (1997). "Effect of Curing on Water Permeability of Concretes Prepared with Normal Portland Cement and with Slag and Silica Fume". *Magazine of Concrete Research*, 49(180), 167-171.

Li Min, Qian Chunxiang, Sun Wei (2002). "The varying rule and the non-destructive measuring of high performance concrete after fire". *Industrial Construction*, 32(10): 34-36.

L. T. Phan (1996). "Fire Performance of High Strength Concrete: A Report of the State-of-the-Art". *Building and Fire Research Laboratory, National Institute of Standards and Technology*, Maryland.

Peng Gaifei, Chen Yannian, Feng Naiqian, et al (1999). "Performance attenuation characteristics of high-strength concrete exposed to high temperatures". *Concrete*, (1): 16-19.

P.K. Mehta (1999). "Advancements in concrete technology". *Concrete International*, 96 (4): 69–76.

Poon C S, Azhar S, Anson M. and Wong Y.-U. (2001). "Comparison of the strength and durability performance of normal-and high-strength pozzolanic concretes at elevated temperatures". *Cement and Concrete Research*, 31 (9): 1291-1300.

Poon CS, Shui ZH, Lam L (2004). "Compressive behaviour of fiber reinforced high-performance concrete subjected to elevated temperatures". *Cement Concrete Research*, 34: 2215-22.

Sanad AM, Lamont S, Usmani AS, Rotter JM (2000). "Structural behaviour in fire compartment under different heating regimes—Part 1 (slab thermal gradients)". *Fire Safety Journal*, 35: 99-116.

Sun Hongmei, Wang Lijiu, Cao Mingli (2003). "Experimental study on strength and durability of high alumina cement concrete after elevated temperature fire". *Industrial Architecture*, 54: 83-91.

Tao Jin, Liu Xian, Yuan Yong (2009). "Transient strain of self compacting concrete at elevated temperature". *Journal of building materials,* 12 (1): 47-51.

Wang Chunhong, Li Xinggui (2003). "Research on the method of improving the durability of concrete". *Construction Technology Development*, 30(9): 107-109.

Yan Zhiguo, Yang Qixin, Zhu Hehua (2005). "Experimental study on temperature field distribution of Changda road tunnel". *Journal of Southeast University*, 35(7): 84-88.

Zhao Tiejun, Ding Jiantong, Zhu Jinquan (1996). "Durability of High Performance Concrete". *Concrete*, (3):